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Study of the Processes of Steam–Hydrogen Mixture Generation in a Reactor for Hydrothermal Aluminum Oxidation for Power Units

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Abstract—This work is devoted to the study of the processes of generation of steam–hydrogen gaseous mixtures formed in the hydrothermal oxidation of aluminum and its further utilization in power units. One of the main objects of this study is a reactor that generates steam–hydrogen mixtures, and the main problem is the continuous mode of its operation. Analytical calculations of thermodynamic parameters that are characteristic of the continuous hydrothermal oxidation of aluminum are reported together with the results of the experimental study of this mode. A combination of theoretical and experimental studies made it possible to determine the composition of aluminum–water suspensions and the range of thermodynamic parameters that are optimal for the continuous reactor of steam–hydrogen mixture generation.

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INTRODUCTION

Aluminum oxidation in water and aqueous solutions has been given considerable attention for the last decades. An interest in this process is due to the high chemical activity of highly dispersed (micrometer-size) aluminum powders in the reactions with water and water vapor. The use of pure water as an oxidant in its reaction with dispersed aluminum makes it possible to synthesize high-purity hydrogen, a large amount of high-temperature steam, and a variety of aluminum hydroxides [1–3]. The main element of the units for hydrothermal oxidation of aluminum by water or steam is a rector that generates a steam–hydrogen mixture, which can be used as a working medium of conventional and future heat engines and generators.

When creating such power engineering complexes, including those from power generation using heat engines base on a generators of the steam–hydrogen mixture (a power source), one of the main problems is to organize a continuum process of a reactor that generates a steam–hydrogen mixture.

Aluminum oxidation with water or steam occurs via the following three reactions. Depending on temperature and pressure, some or all of them may occur, and the intensity of each may vary:

$$2Al + 3H_2O \longrightarrow Al_2O_3 + 3H_2,$$
$$2Al + 3H_2O \longrightarrow Al(OH)_3 + 1.5H_2, \quad (1)$$

$$Al + 2H_2O \longrightarrow AlOOH + 1.5H_2. \quad (2)$$

Under hydrothermal conditions, the process of aluminum conversion into monoxides and oxides usually occurs via the step of $Al(OH)_3$ formation. Thermodynamic calculations of aluminum hydroxide dehydration under hydrothermal conditions were car-

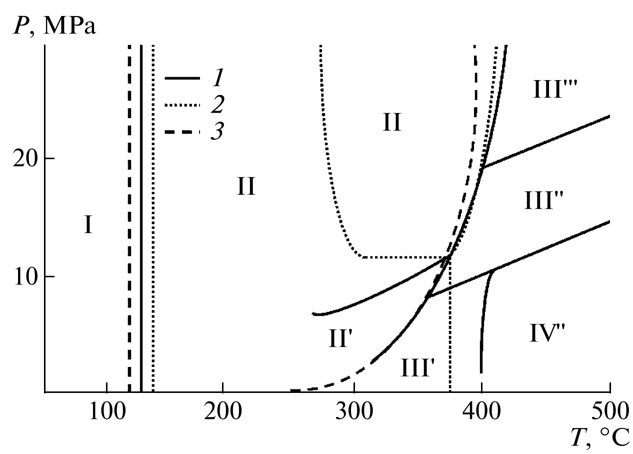

Fig. 1. Experimental and calculated diagrams of transformation in the Al_2O_3–H_2O system under hydrothermal conditions: (*1*) experimental diagram [5], (*2*) experimental diagram [6], (*3*) calculated diagram [4]; I is the region of $Al(OH)_3$ (gibbsite) existence [7], II is the region of stable existence of diaspore (α-AlOOH) [7], II' is the region of existence of metastable boehmite (γ-AlOOH) [7], III' is the region of existence of α-Al_2O_3 (nanocrystalline) [6], III'' is the region of existence of α-Al_2O_3 (KI form) [6], III''' is the region of existence of α-Al_2O_3 [6], IV is the region of existence of α-Al_2O_3 [8].

ried out in [4], where $Al(OH)_3$ was taken as an initial compound. Figure 1 shows the calculated diagrams of conversions in the Al_2O_3–H_2O system under hydrothermal conditions and experimental data of several researchers.

Analysis shows that experimental data and the results of calculations are very close [4, 8, 9]. The only systematic difference between the calculated and experimental data is that, although theoretically the most stable modification of oxyhydroxide in region II in the whole range of AlOOH existence is α-AlOOH (diaspore), all experiments revealed only γ-AlOOH (boehmite). This can be explained by the fact that boehmite formation is kinetically preferable compared to diaspore formation because it does not require considerable reconstruction of the crystalline lattice in the course of the dehydration of intermediate compounds. Therefore, according to Buerger's classification, this reaction is fast [8].

A complex physicochemical study of the products of hydrothermal treatment [4] allowed us to determine a general scheme of dehydration processes under high pressures

$$\left.\begin{array}{l} Al(OH)_{3\,\mathrm{cryst}} \\ Al(OH)_{3\,\mathrm{am}} \end{array}\right\} \longrightarrow AlOOH_{\mathrm{boehmite}} \longrightarrow \alpha\text{-}Al_2O_3.$$

However, for the design of a reactor for generating a steam–hydrogen mixture by the reaction between aluminum and water under hydrothermal conditions, one has to know the general scheme of transformations, the compositions and thermophysical characteristics of the reaction products for different ratios of reactants and reaction conditions.

It is also noteworthy that the formation of corundum in aluminum oxidation under hydrothermal conditions at temperatures of 380–400°C causes serious engineering problems. The high rates of oxidation of low-dispersity aluminum in this range of temperatures and pressures in the closed volume of the reactor make it impossible to control the reactor temperature. Corundum agglomerates destroy cut-off devices and block up exit pipelines for the steam–hydrogen mixture and aluminum hydroxides as soon as these agglomerates are formed.

In this article, we report the results of calculations of thermodynamic parameters in the reactor for hydrothermal aluminum oxidation at temperatures below 400°C, which are necessary for the continuous generation of a steam–hydrogen mixture and AlOOH, calculation of the reactor volumes taking into account the kinetics of aluminum oxidation in high-temperature wet saturated vapor. We also report the results of experiments on the mode of continuous operations of the reactor for generating a steam–hydrogen mixture.

CALCULATIONS AND AN ANALYTICAL STUDY

The equilibrium composition of the products of hydrothermal aluminum oxidation was calculated using an Excel-based code adapted to temperatures of 300–500°C and pressures of 0.1–15 MPa. Initial data for the calculation of the composition and thermodynamic properties of the system were taken from IVTANTHERMO database of individual substances [10].

The products of aluminum reaction with water under hydrothermal conditions are liquid water and its vapor, hydrogen, and aluminum hydroxides, which are collected in the reactor bottom. When hydroxides exit the reactor, water with high heat content also leaves the reactor. This leads to a decrease in the fraction of thermal energy evolved in the reactor for the use as power. To minimize the loss of thermal energy, we carried out calculations of the distribution of thermal energy flows exiting in the reactor under conditions of its continuous operation. We did not take into account heat loss through the reactor walls. Taking this into account, the optimal ratio of water and aluminum in the above-mentioned range should be corrected in each particular case.

Conditions for the continuous operation of the reactor are as follows:

—mass balance ($m_{in} = m_{out}$, that is, the overall mass of suspension supplied to the reactor per unit time must be equal to the mass of the reactor products leaving the reactor per unit time);

—energy balance ($Q_{in} = Q_{out}$, that is, energy formed by the chemical reaction in the reactor per unit time should be consumed for maintaining constant thermodynamic conditions in it).

It as commonly assumed that all energy of the reaction is completely consumed for maintaining the continuous mode of operation no matter where it is specifically formed in the reactor. The temperature inside the reactor is assumed to be approximately the same in the whole volume.

Figure 2 illustrates the supply of reagents into the reactor and the exit of products. A suspension of low-dispersity aluminum powder in water is supplied from top through nozzles using a dosing pump. The outlet of gaseous products is in the upper part of the reactor and the bottom has the outlet for the solid and liquid phases.

Let us introduce a parameter α that is a ratio of the water mass to the mass of aluminum in suspension supplied to the reactor per unit time. Then, if the consumption of aluminum is m, the consumption of water is αm. The overall flow into the reactor is $m + \alpha m$. It is obvious that the overall mass removed from the reactor per unit time must also be $m + \alpha m$. If the reaction occurs via the pathway of boehmite formation, then there is a mixture of boehmite and water in the liquid

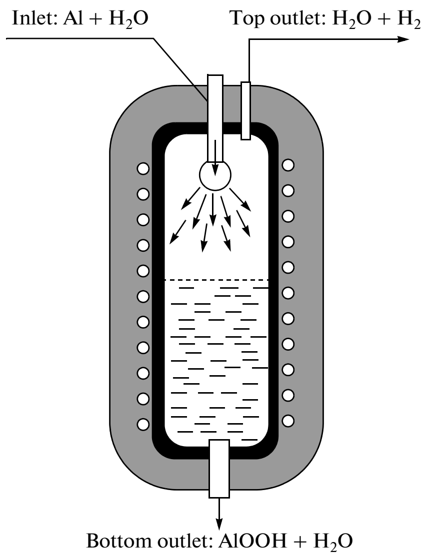

Fig. 2. Schematic of the reactor.

phase at the bottom outlet and a mixture of hydrogen and water at the outlet on the top. According to reaction (2) every m kg of Al forms $2.22m$ kg of boehmite and $0.11m$ kg of hydrogen.

Then, let us assume that, in each moment of time, the reactor contains wet saturated water vapor. The dryness of steam X is

$$X = \frac{\text{weight of dry saturated steam}}{\text{overall weight of wet steam}} = \frac{m''}{m' + m''}.$$

Under conditions of continuous mode, the following condition should be met:

$$X(t) = \frac{m''}{m' + m''} = \text{const}. \quad (3)$$

The dryness of steam X depends on the thermodynamic conditions in the reactor (T or P) and α.

Under conditions when the reactor is continuously supplied with the reactants, the yield of reaction product is determined by the following parameters: m, the weight of aluminum supplied to the reactor; α, the ratio of the weight of water to the weight of aluminum; T, temperature; and P, pressure in the reactor.

The weight of aluminum supplied to the reactor is a quantitative parameter, and it does not affect α, T, and P. On the contrary, parameters α, T, and P depend on each other so that any two of them uniquely define the third. Therefore, in calculations one has to define any two of these three parameters. In our calculation we chose m, α, and T.

By setting m, α, and T, one can calculate the values of mass flows of reaction products that leave the reactor on the top and on the bottom and P at which continuous mode with given m, α, and T is possible.

Then, knowing the mass flows of reaction products on the top and on the bottom, one can determine the rate of heats removed at the respective outlets.

To find the pressure and the mass flows of products, it is necessary to determine, the fraction of evaporated water, which leaves the reactor on the top, and the fraction of water in the liquid phase, which leaves the reactor together with boehmite at given T and α. Let us write the energy balance equation:

$$Q_{\mathrm{in}} = C_{\mathrm{Al}} m(T - T_0) + \alpha m(i' - i_0) + m''(i'' - i'), \quad (4)$$

where C_{Al}l is the average thermal capacity of aluminum in the given temperature range; i_0 is the water enthalpy at temperature T_0; i'' is the enthalpy of dry saturated vapor; i' is the enthalpy of water at temperature T; $C_{\mathrm{Al}} m(T - T_0)$ is the amount of heat that is necessary to heat the mass m of aluminum from temperature T_0 to T; $\alpha m(i' - i_0)$ is the amount of heat necessary to heat the mass αm of water from temperature T_0 to T; and $m''(i'' - i')$ is the amount of heat that is necessary for evaporating the mass m'' of water at temperature T.

In the calculations we used the thermodynamic properties of water and vapor from [4].

The energy balance in the form of Eq. (4) assumes that the continuous mode also meets condition (3) (that is, on the T–S diagram, the state of vapor in the reactor corresponds to a point within the limits of the saturation curve on the so-called "ledge").

Q_{in} is the energy evolved for one second (power) in the reactor in the course of aluminum oxidation. It can be written that $Q_{\mathrm{in}} = qm$ is the loss, where q is the reaction enthalpy, and the loss can be due to the dissipation of heat on the walls of the reactor and incompleteness of aluminum oxidation. As shown above, q depends on temperature, an at 300–360°C, the reaction enthalpy is 4–6% higher than at room temperature. For the reaction that occurs at 300–360°C, the enthalpy may be higher than 16 MJ/kg Al in the case of complete oxidation of aluminum.

According to Eq. (4), heat formed during the reaction should be consumed for heating the suspension to temperature T which is kept constant in the reactor in the continuous mode (the first two terms in (4)) and for evaporating part of water (the last term in (4)). Obviously, that the amount of evaporated water for 1 s is the same as that leaving the system.

Model used in Eq. (4) assumes that the suspension is initially heated to temperature T of the reactor and then the reaction occurs, and boehmite and hydrogen formed already have this temperature. In fact, aluminum oxidation begins at temperatures lower than T, boehmite is formed and then it is further heated to T. In this sense, Eq. (4) is the boundary model.

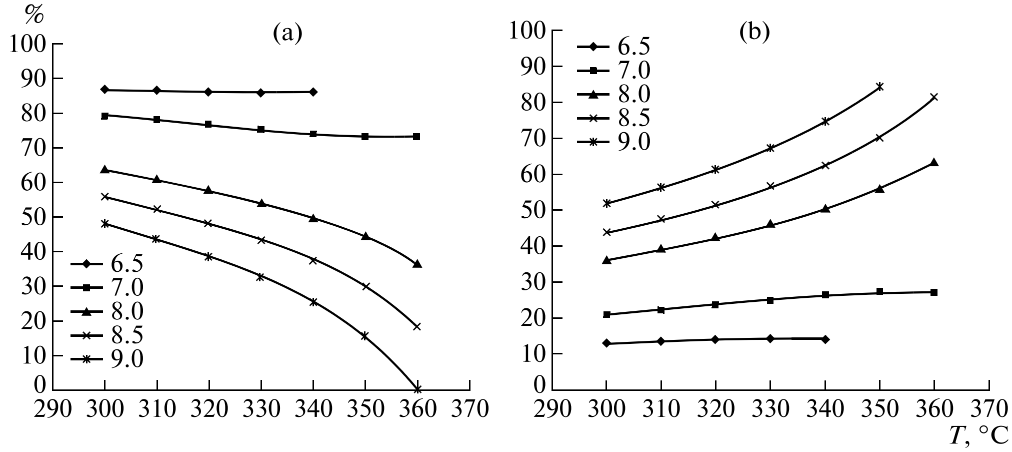

Fig. 3. The distribution of thermal energy discharged from the reactor together with (a) the steam-hydrogen mixture, (b) aluminum hydroxide for the Al/H_2O ratios in the initial suspension.

Another boundary model is the opposite: the reaction occurs at room temperature, and boehmite and hydrogen are heated to temperature T:

$$Q_{in} = C_{boehmite} \times 2.22m(T - T_0) + C_{H2} \times 0.11m(T - T_0) + (\alpha m - 1.33m)(i' - i_0) + m''(i'' - i'),$$

where $C_{boehmite} \times 2.22m(T - T_0)$ is the amount if heat necessary for heating $2.22m$ of boehmite from T_0 to T; $C_{H2} \times 0.11m(T - T_0)$ is the amount of heat necessary for heating $0.11m$ of hydrogen from T_0 to T; and $(\alpha m - 1.33m)(i' - i_0)$ is the amount of heat necessary for heating $\alpha m - 1.33m$ of water from T_0 to T.

From the standpoint of balance calculations, there is no difference between these models. However, if one takes into account reaction kinetics, model (4) describes patterns that are closer to real. Most of aluminum reacts with water only when heated to a temperature of ~300°C.

It follows from Eq. (4), that the weight of water that is evaporated and removed on the top that is

$$m'' = \frac{q \times m - C_{Al} \times m \times (T - T_0) - \alpha m \times (i' - i_0)}{(i'' - i')},$$

and the weight of water removed together with boehmite is

$$m' = \alpha m - 1.33m - \frac{q \times m - C_{Al} \times m \times (T - T_0) - \alpha m \times (i' - i_0)}{(i'' - i')}.$$

These calculations led us to conclude that there is a continuous mode corresponding to given temperature T and the coefficient of water excess α.

If m'' and m' are positive, then the continuous mode under condition (3) is theoretically possible at given T and α.

If one of these values is negative, then the continuous mode is impossible under condition (3) at corresponding T and α. Energy evolved in the course of the reaction is insufficient for maintaining constant temperature in the reactor, and this contradicts the condition of energy balance of the continuous mode.

The mass flow rates of products of hydrothermal aluminum oxidation on the top and bottom of the reactor in the continuous mode of reactor operation under condition (1) for the corresponding T and α are determined by the following expressions: the flow rate on the bottom is $(m' + m_{boehmite})$ kg/s and the flow rate on the top is $(m'' + m_{H2})$ kg/s.

The dryness of boehmite is $m_{boehmite}/m'$. The amount of heat removed from the reactor is

$$Q_{bottom} = C_{boehmite} \times 2.22m(T - T_0) + m'(i' - i_0),$$

$$Q_{top} \approx C_{H_2} \times 0.11m(T - T_0) + m''(i'' - i_0).$$

The reactor pressure consists of the partial pressures of water vapor and hydrogen:

$$P = P_{sat.vap.} + P_{H_2}, \quad P_{sat.vap.}V = (m''/M_{H_2O})RT, \tag{5}$$

where M_{H2O} is the molecular weight of water, and

$$P_{H_2}V = (m_{H_2}/M_{H_2})RT, \tag{6}$$

where M_{H_2} is the molecular weight of hydrogen.

By dividing (5) by (6) and expressing P_{H2} through $P_{sat.vap.}$, we obtain for the overall pressure the following expression:

$$P = P_{sat.vap.} + P_{H_2} = P_{sat.vap.} \times [1 + (0.11m/M_{H_2})(M_{H_2O}/m'')].$$

Proceeding from the results of calculations shown in Fig. 3, once can conclude that, from the standpoint of energetics and temperature in the reactor for hydro-

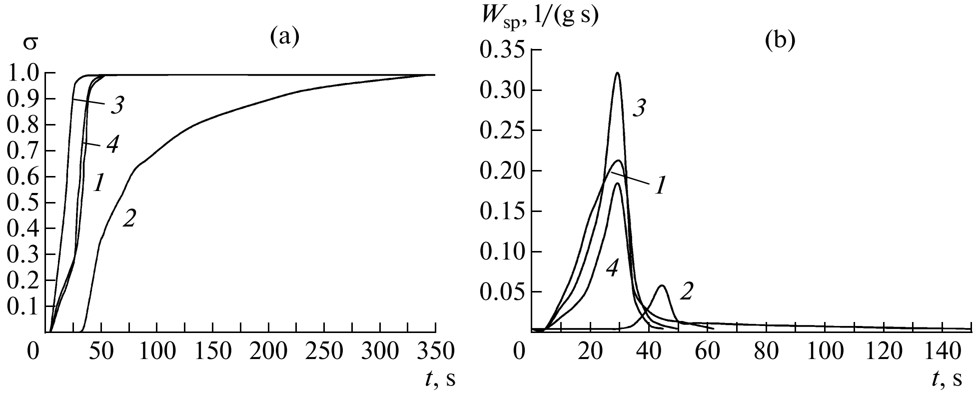

Fig. 4. Dependences of the (a) aluminum oxidation state and (b) specific rate of hydrogen formation on time for the suspensions: (*1*) ASD-6 + H_2O powder, (*2*) ASD-4 + H_2O powder, (*3*) ASD-6 + H_2O + 0.1 wt % NaOH powder, (*4*) ASD-4 + H_2O + 0.1 wt % NaOH powder.

thermal aluminum oxidation at which the process occurs without corundum formation, the optimal ratio between aluminum and water in the initial suspension is Al/H_2O = 7.5–8.5. The temperature in the reactor is within the range 320–350°C, and the fraction of thermal energy in the form of steam that leaves the reactor together with hydrogen will be 50–60% of the overall thermal energy formed by the reaction.

When choosing the volume of the reactor for generating hydrogen, it is necessary to take into account that it has to be sufficient for an aluminum particle to stay until its complete conversion into aluminum hydroxide before it would leave the reactor. The reactor volume largely depends on time for the complete oxidation of aluminum (Fig. 4), on the type of powder used, and on the flow rate of suspension in the reactor feed (Fig. 5).

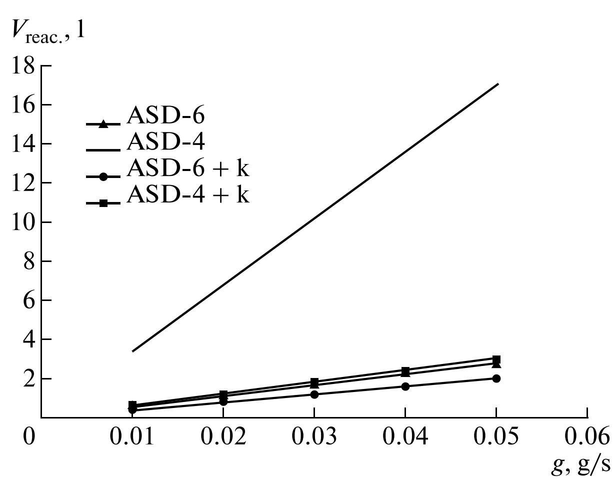

Fig. 5. Dependence of the reaction volume on the composition of the initial suspension and its flow rate in the reactor feed.

Figure 4 shows the experimental results of the kinetic study of aluminum powders with different dispersities under hydrothermal conditions [10].

One can see that the complete oxidation of aluminum under hydrothermal conditions becomes possible in a certain time after its supply to the reactor. Table 1 shows experimental values for the duration of this period of time for various aluminum powders in the composition of initial suspension of reactants at an Al/H_2O ratio of 1/8.

The authors of [10] found a positive effect of adding 0.1 wt % NaOH to the aluminum–water suspension. In addition to the increase in the rate of the reaction between water and aluminum fraction with larger particles, this additive led to a decrease in the size of boehmite particles from 1 to 0.1–0.2 μm. This makes it easier for aluminum hydroxides to leave the reactor.

EXPERIMENTAL

The experimental study of the technology for the continuous generation of steam–hydrogen mixture was carried out using a reactor with a volume of 7 l. The reaction volume was 4.5 l.

The filling of the reactor was controlled using an IUB-1K isotopic level meter. The operation principle of level meter is based on the monitoring of changes in the γ ray flow density where the sensor zone of the detection unit set up in the controlled volume is located. These changes are due to the changes in the level of material that fills the volume. The flow of γ rays from the elongated emitter is weakened by the controlled material and is recorded by a detection unit, in which it translates into a series of statistically distributed pulses with a certain frequency, which is proportional to the flow density of irradiation. As the level of controlled material increases, the flow of γ rays from the lower part (which increases with an increase in the level) of the elongated emitter weakens. To maintain

Table 1. Time of the complete oxidation of aluminum for various compositions of the initial suspensions

Composition of the suspension	ASD-6, H_2O	ASD-4, H_2O	ASD-6, H_2O, 0.1% NaOH	ASD-4, H_2O, 0.1% NaOH
Time of the complete oxidation, s	55	320	40	60

relative linearity of this inverse dependence of the flow density (and, correspondingly, the frequency of pulses) on the level, the activity of local sources in an elongated emitter decreases along its height. The output signal of the recording unit is 4–20 mA.

Figure 6 shows the reactor unit of the setup.

The high-pressure dosing pump (H_2) used in the setup allows a maximum flow of 36 g/s. Hydroxide suspension leaves the reactor via the bottom nozzle and the steam–hydrogen mixture leaves the reactor through a top nozzle. To let the products exit the reactor at such flow rate through the bottom nozzle of the reactor at a pressure of 15–17 MPa and a temperature of 300–350°C, a throttling device with a small cross section is necessary. The modeling of a throttling device for a complex multiple-phase medium containing water vapor, hydrogen, and a suspension of boehmite in water is currently impossible. We obtained experimental values of the flow rates of the steam–hydrogen mixture at T = 300–350°C and P = 15–17 MPa through the nozzles with various cross sections, which can be reference when choosing the values of cross sections of the throttling device for discharging the mixture of aluminum hydroxides, water, water vapor, and hydrogen from the reactor. Table 2 shows the results of these measurements.

At this stage of experiments, we chose for the initial mixture of reactants a suspension containing ASD-6 aluminum powder and water at a ratio of 1/8 with 0.1 wt % NaOH added. This choice was due to the highest specific rate of aluminum oxidation and by the smaller aggregates of boehmite particles compared to other compositions in our reactor for hydrothermal oxidation. In the reactor for hydrothermal oxidation of aluminum, optimal conditions were maintained (T = 320–350°C; P = 12–17 MPa) for the well-controlled synthesis of hydrogen and low-dispersity boehmite powder.

The following algorithm was used in the experiments:

– preliminary heating of the reactor to a temperature of 320°C;

– continuous supply of the reactant suspension with a flow rate of 30 g/s;

– the discharge of steam–hydrogen mixture through the top nuzzle with a diameter of 0.8 mm is continuous during a run when the pressure becomes 17 MPa;

– the discharge of aluminum hydroxide suspension into a boehmite collecting vessel is periodical: it starts when a certain level L_{max} of the water-aluminum mixture is achieved in the reactor according to a IUB-1K level meter and ends when the level becomes L_{min};

– dried hydrogen is continuously discharged into a cylinder manifold;

– the condensate is discharged discretely as accumulated.

The time of continuous operation was limited by the volume of the receiving vessel of aluminum hydroxides, which had not been equipped with automatic device for their discharge.

Figure 7 shows the results of experiments. The following values were determined: the average flow rate of the steam discharged from the reactor $G(H_2O)$= 10.7 g/s and the average flow rate of hydrogen $G(H_2)$ = 3.8 l/s = 0.4 g/s. The overall flow rate of the mixture was 11.1 g/s.

The flow of the steam–hydrogen mixture from the reactor can be estimated from the initial data of this run according to the known gas dynamic expression

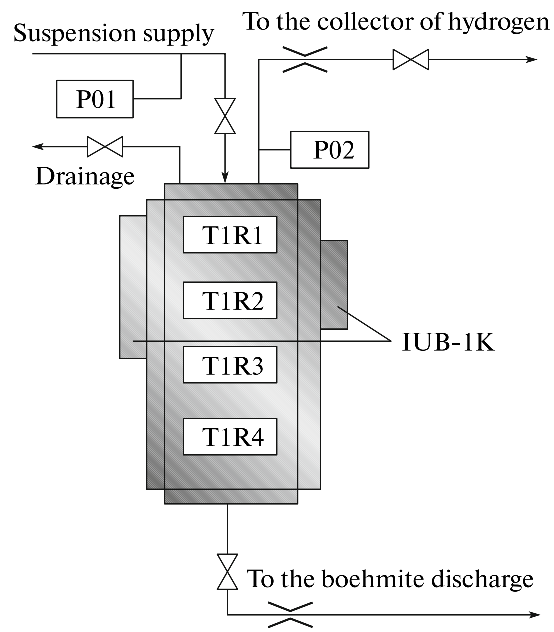

Fig. 6. Schematic of the reactor unit. T1R1, T1R2, T1R3, and T1R4 are the thermocouples of the reactor; P01 is the pressure sensor at the inlet of the reactor; and P02 pressure sensor inside the reactor.

Table 2. Flow characteristics of nuzzle for the pipline of boehmite and water discharge

Ø, mm	0.6	0.7	0.8	1.0
Q, g/s	30	38	46	52

for the critical flow through an nozzle with cross section F:

$$G = NFP/(RT)^{0.5}, \tag{7}$$

where P, R, and T are the pressure, universal gas constant, and temperature of the steam–hydrogen mixture in the reactor, and N is the coefficient:

$$N = \sqrt{k\left(\frac{2}{k+1}\right)\frac{k+1}{k-1}}.$$

Taking into account that moisture exists in the form of steam, and the mass fraction of moisture in the mixture $g(H_2O)$ is 0.942 and the mass fraction of hydrogen $g(H_2)$ is 0.058.

The gas constant of the mixture is determined from the expression

$$R_g = R(H_2O)g(H_2O) + R(H_2)g(H_2) = 673.92\ \mathrm{J/(kg\ K)}.$$

Here the gas constants of steam and hydrogen are $R(H_2O) = 461.5$ J/(kg K) and $R(H_2) =4124$ J/(kg K).

The specific heat capacity of the mixture is determined from the expression

$$C_{pg} = C_{pv}g(H_2O) + C_{ph}g(H_2) = 5370\ \mathrm{J/(kg\ K)}.$$

The values of the specific heat capacity of steam and hydrogen at the parameters of the reactor are $C_{pv} = 4815$ J/(kg K) and $C_{ph} = 14400$ J/(kg K), respectively.

The ratio of specific heats can be found from the expression $k = 1/(1 - R_g/C_{pg})=1.14$, and the coefficient N as a function of k is 0.6356 [11].

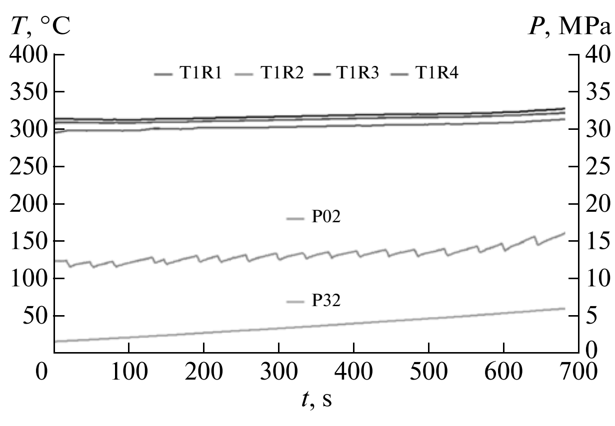

Fig. 7. Temperature and pressure changes with time in the reactor of hydrogen generation in a continuous mode: T1R1, T1R2, T1R3, and T1R4 are the temperatures inside the reactor; P02 is the pressure inside the reactor; and P32 is the pressure in the hydrogen ramp.

The cross section area of the nozzle at a hole diameter of 0.8 mm is $F = 5 \times 10^{-7}\ 7\ \mathrm{m}^2$.

According to (7), for our experimental conditions, the critical flow of the steam–hydrogen gaseous mixture through a nuzzle is 8.9 g/s. The difference between the calculated and measured values of the steam–hydrogen flow can be explained by the presence of condensed moisture in the mixture.

The average flow of the water–boehmite mixture discharged from the reactor was 13.8 g/s.

Analysis of experimental data shown in Fig. 7 suggests that continuous mode of operation of a reactor for generating a steam–hydrogen mixture is possible under the above experimental conditions. The temperature and pressure in the reactor are rather stable for 10 min of a run. Variations in the pressure in the reactor P_{02} due to periodical discharge of boehmite and water are at most 10%. Better stability of temperature and pressure in the reactor can be achieved by the better optimization of the ratio between aluminum and water in the initial mixture.

In the reaction products we have not found aluminum and thus concluded that the oxidation process is largely complete.

CONCLUSIONS

1. A complex of theoretical and experimental studies made it possible to determine the composition of suspensions of aluminum powder in water and the range of thermodynamic parameters of the process of hydrothermal aluminum oxidation for creating continuous reactors for the generation of steam–hydrogen mixture.

2. The technology of continuous mode of operation of the reactor for generating a steam–hydrogen mixture was experimentally tested for a reactor volume of 7 l. The temperature inside the reactor for hydrogen generation was kept constant in the range 300–340°C and a pressure of $P = 12$–15 MPa during its operation. The absence of nonoxidized aluminum in the composition of reaction products confirms the correctness of engineering ideas in the development of technology for continuous mode of reactor operation.

3. The results obtained can be used in the design of energy units for the production of thermal and electric energy.

REFERENCES

1. Mazalov, Yu.A., Bersh, A.V., and Ivanov, Yu.L., *Sposob polucheniya gidroksidov ili oksidov alyuminiya i vodoroda i ustroistv dlya ego osushchestvleniya*, RF Patent 2278077.
2. Bersh, A.V., Kleimenov, B.V., Mazalov, Yu.A., and Nizovtsev, V.E., *Informost Radioelektronika i Telekommunikatsii,* 2005, no. 38, p. 62.

3. Kleimenov, B.V., Mazalov, Yu.A., Bersh, A.V., and Nizovtsev, V.E., *Informost Radioelektronika i Telekommunikatsii*, 2005, no. 39, p. 58.
4. Al'myasheva, O.V., Korytkova, E.N., Maslov, A.V., and Gusarov, V.V., *Neorg. Mater.*, 2005, vol. 41, no. 5, p. 540.
5. Toropov, N.A., Barzakovskii, V.P., Lapin, V.V., and Kurtseva, N.N., *Diagrammy Sostoyaniya Silikatnykh Sistem: Spravochnik* (Phase Diagrams of Silicate Systems: A Handbook), Moscow: Nauka, 1965.
6. Buerger, M.J., *Fortsher. Miner*, 1961, vol. 39, p. 9.
7. Laubengayer, A.W. and Weiss, R.S., *J. Am. Chem.Soc,* 1943, vol. 65, no. 2, p. 247.
8. Erwin, G. and Osborn, E.F., *J. Geol.*, 1951, vol. 59, no. 4, p. 381.
9. Mazalov, Yu.A., Bersh, A.V., Lisitsyn, A.V., et al., *Tekhnika v sel'skom Khozyaistve*, 2007, no. 2, p. 30.
10. Iorish, V.S., Belov, G.V., and Yungman, V.S., *Programmnyi kompleks IVTANTERMO dlya WINDOWS i ego ispol'zovanie v prikladnom termodinamicheskom analize. Preprint no. 8415* (Program package IVTANTERMO for Windows and Its Use in Applied Thermodynamic Analyis), Moscow: Joint Inst. for High Temperatures, Russian Academy of Sciences,1998.
11. Abramovich, G.N., *Prikladnaya gazovaya dinamika* (Applied Gas Dynamics), Moscow, 1969.